High Gradient Induction Linac R&D at LLNL*

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Fermi National Accelerator Laboratory
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* Patents Pending. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

A new type of induction accelerator promises to provide increased gradient for a number of applications

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- Dielectric Wall Accelerator (DWA) for flash x-ray radiography
- Important technologies for the DWA
  - High gradient insulator technology
  - Blumlein development
  - Solid-state switch development
  - Dielectric materials
- Proton therapy concept
- Summary

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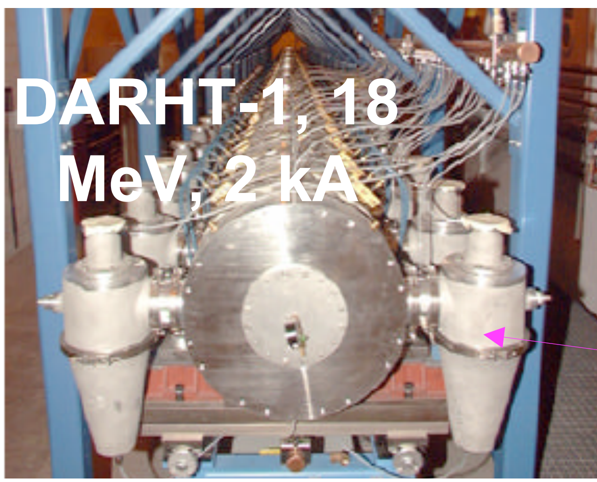
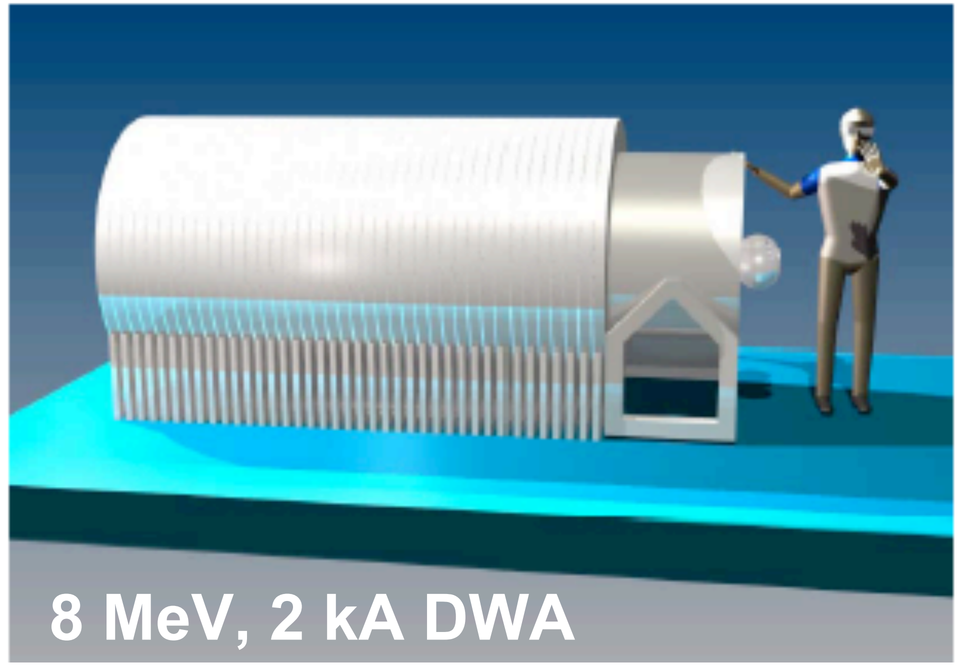
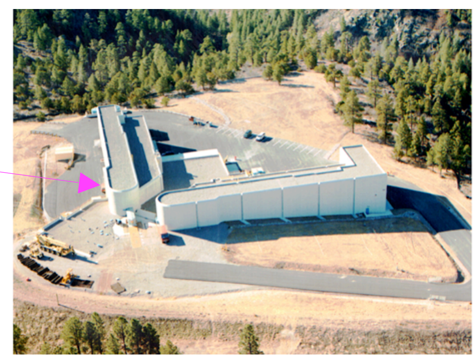
DWA technology originated with a desire for more compact flash x-ray sources







- existing LIA sources have gradients < 0.5 MV/m

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Dielectric Wall Accelerator (DWA) incorporates pulse forming lines into a high gradient cell with an insulating wall

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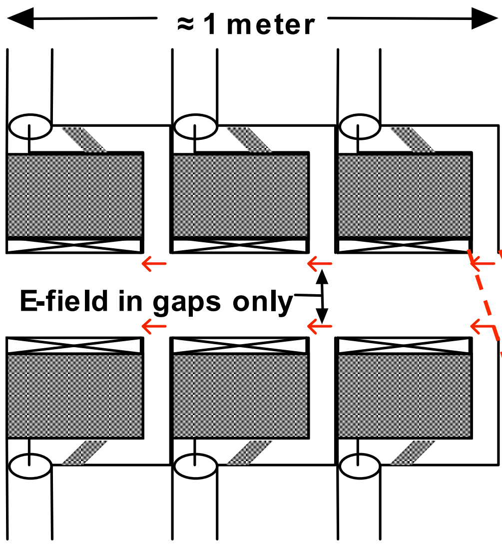
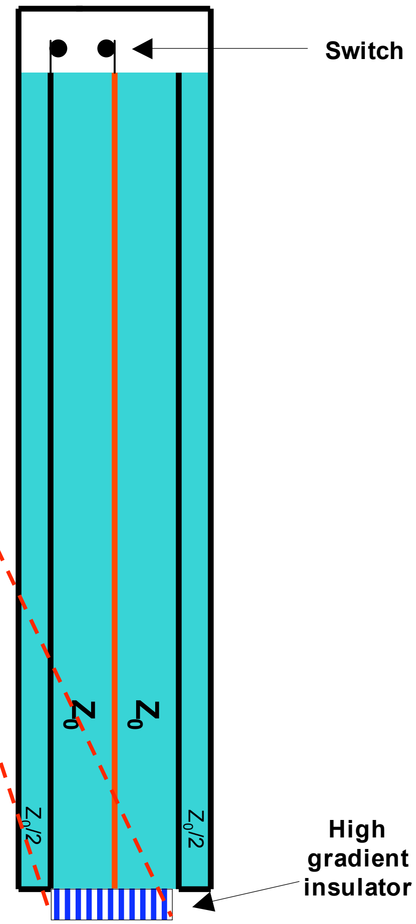
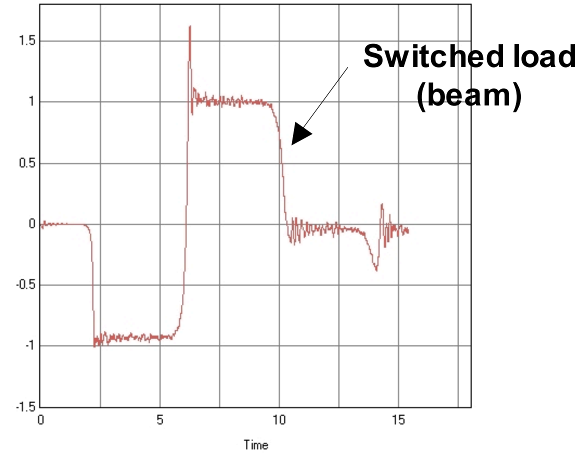


State of the Art Electron Induction Accelerator
≈ 0.3 - 0.5 MV/meter Gradient



Novel Zero Integral Pulse (ZIP) Forming Line with potential for > 10 MV/m*



Important elements for the DWA

- High gradient insulators
- PFL architecture
- Switches
- Large size dielectrics with high dielectric constant and high bulk breakdown strength

* Patent Pending

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High gradient insulators (HGIs) perform 2 - 5 x better than conventional insulators*

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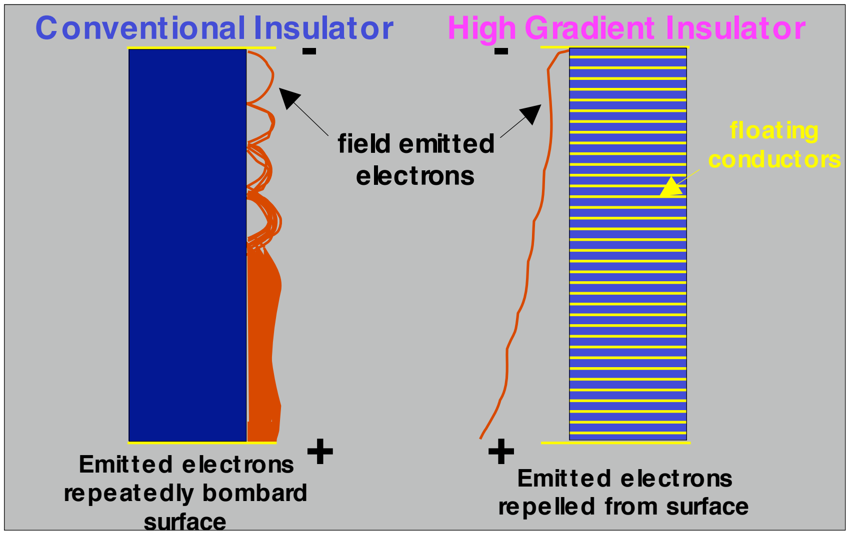
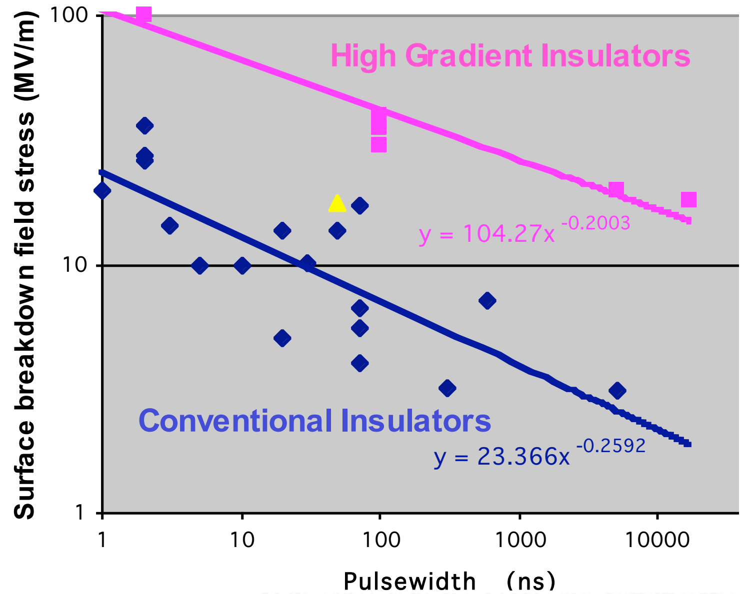
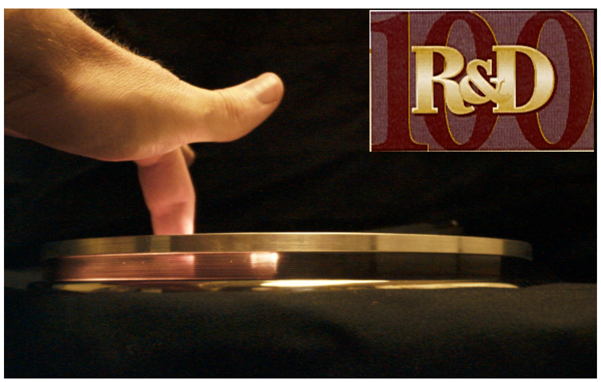
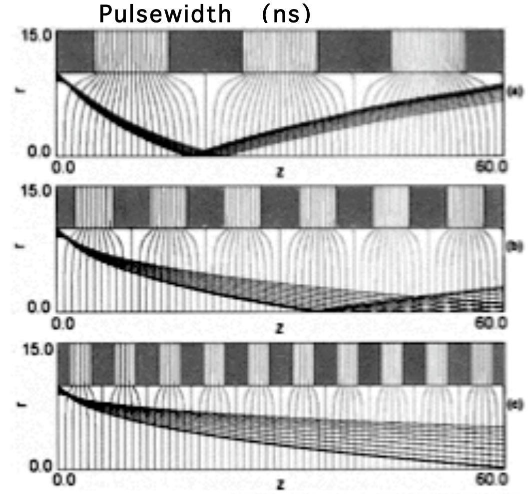


Closely spaced conductors inhibit the breakdown process





HGI structure forms a periodic electrostatic focusing system for low energy electrons



Leopold, et. al., IEEE Trans. Diel. and Elec. Ins. 12, (3) pg. 530 (2005)

* U. S. Patent No. 6,331,194

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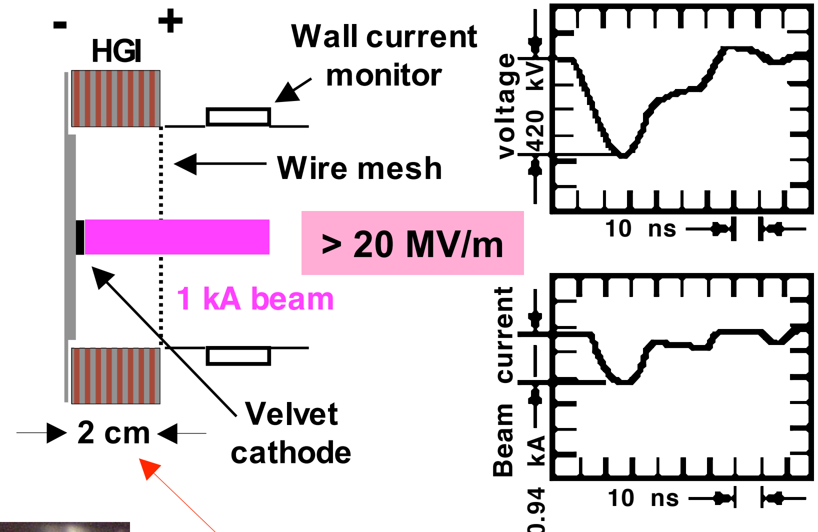
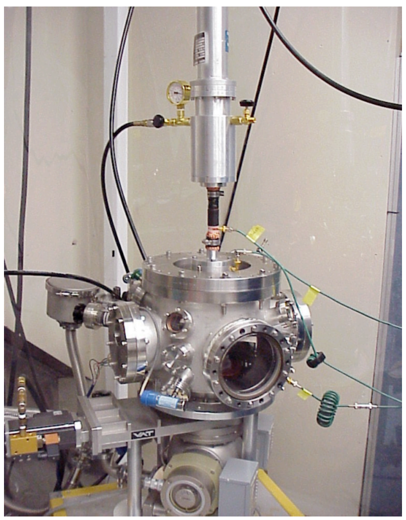
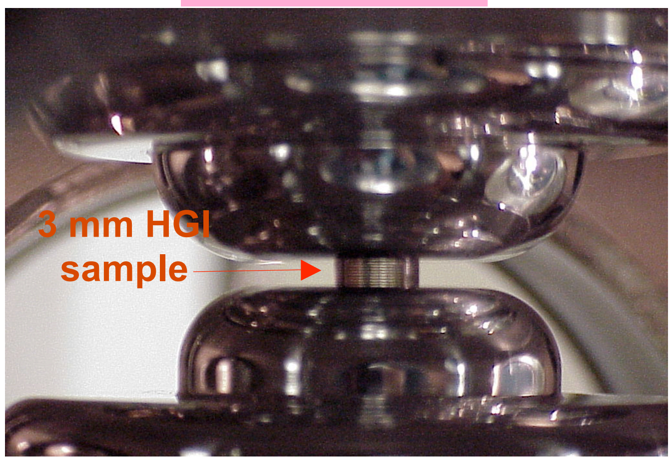
HGIs have withstood extreme conditions

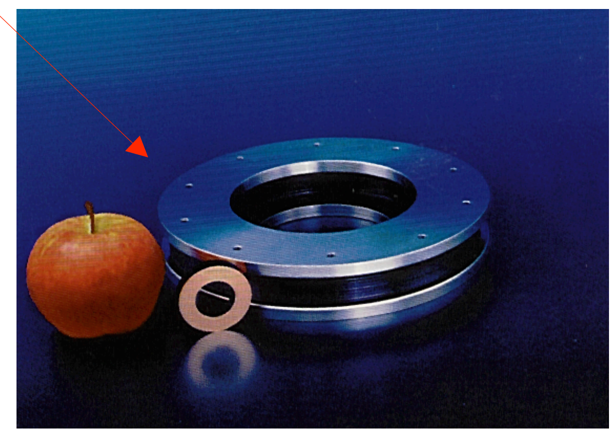
- On ETA-II (5.3 MeV, 2 kA, 50 ns pulses)
- 17 MV/m insulator gradient
- Beam dump in vicinity of insulator
- Line of sight to beam





100 MV/m, 3 ns





A basic pulse generator is formed from two transmission lines

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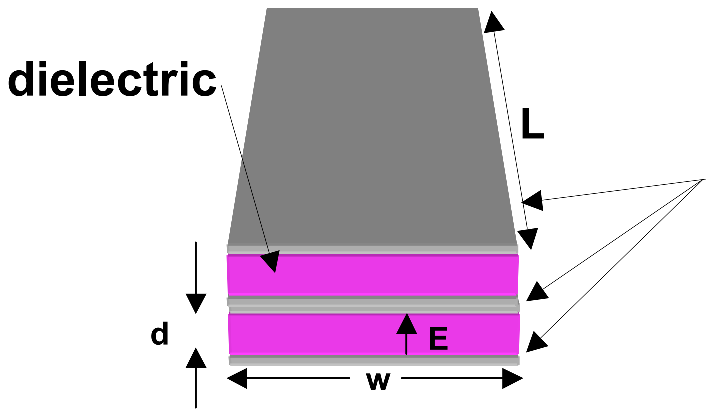
All DWA configurations employ parallel plate transmission lines



One way transit time in each line $\tau = \frac{L}{c}\sqrt{\varepsilon_r}$

Impedance of each transmission line $Z = \frac{120\pi}{\sqrt{\varepsilon_r}}\frac{d}{w}$

Typical current flow in the line with a gradient E $I = \frac{V}{Z} = \frac{Ed}{Z} = \frac{\sqrt{\varepsilon_r}wE}{120\pi}$

Example: E = 50 MV/m, w = 1 cm, ε_r = 3 => 2.3 kA

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Operation of a basic Blumlein pulse generator

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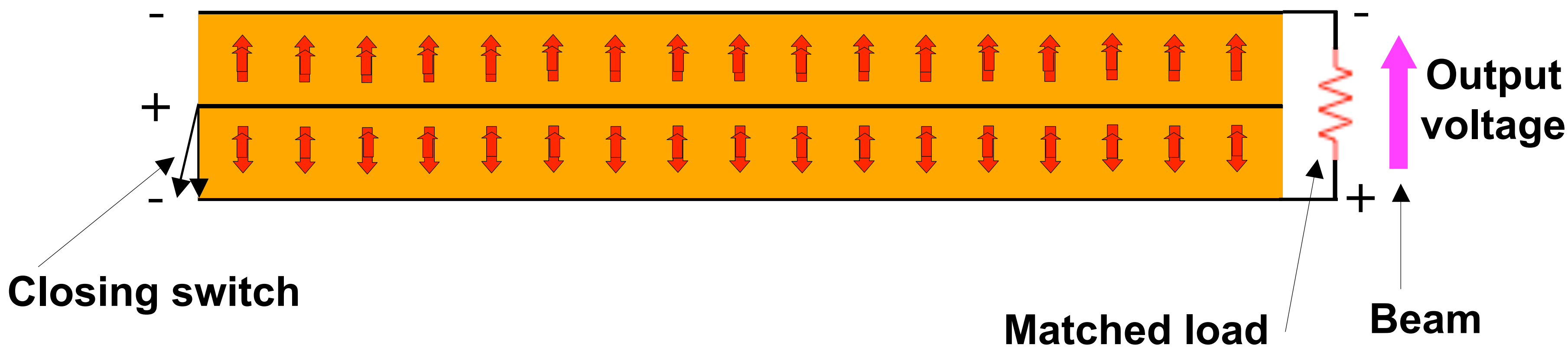

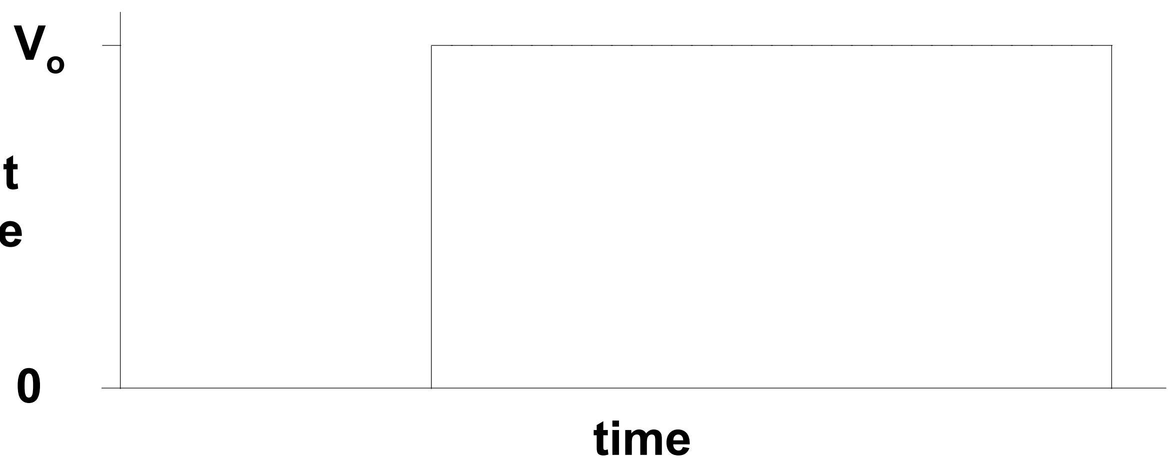

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Oil switch/Polypropylene Blumlein has achieved 100 MV/m stress in transmission lines for 5 ns pulses

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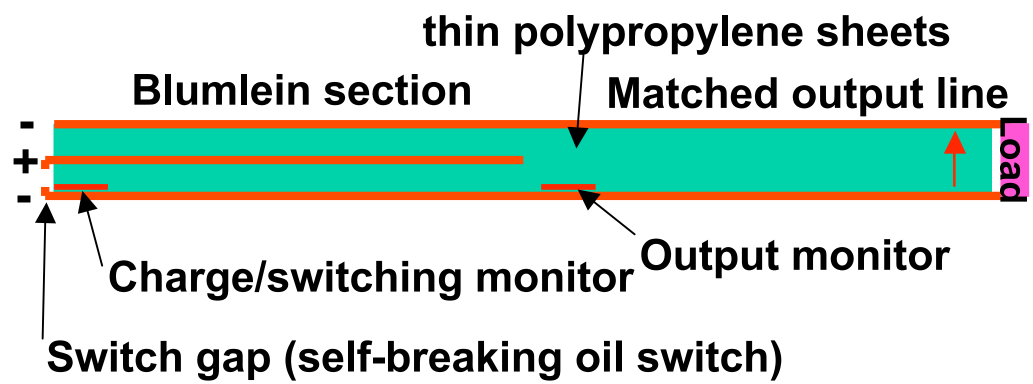
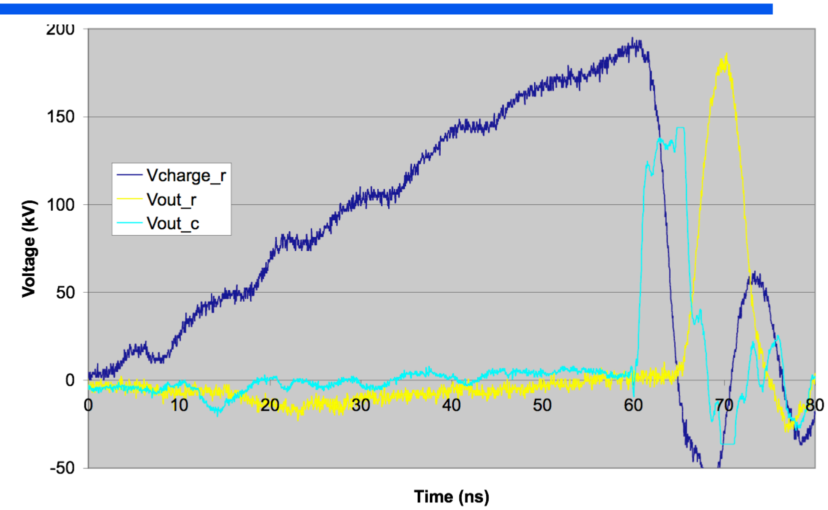
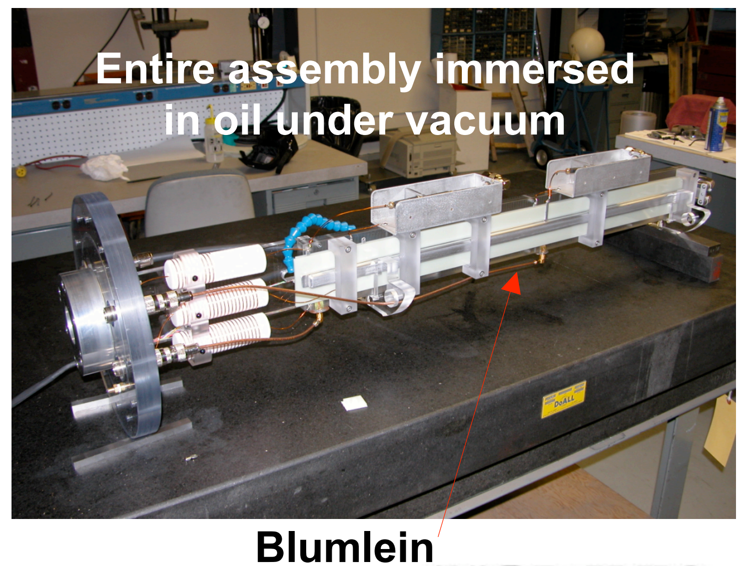
Blumlein provides electric field across the load (HGI)





Goal is to replace oil switch with a solid state switch and polypropylene with cast dielectric



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SiC photoconductive switches offer unique advantages*

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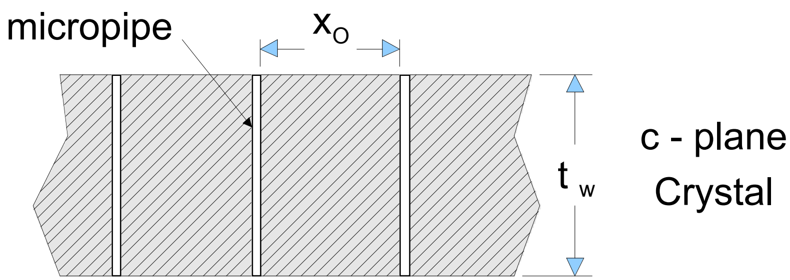

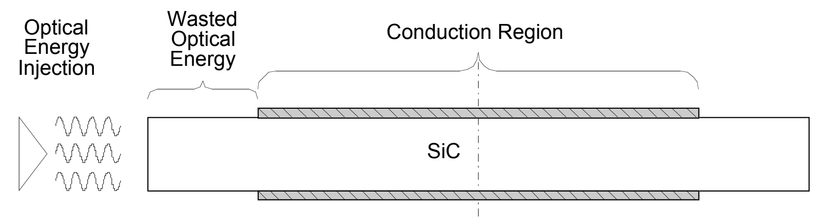

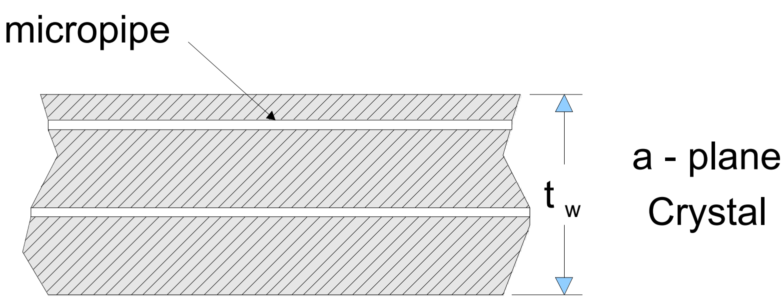

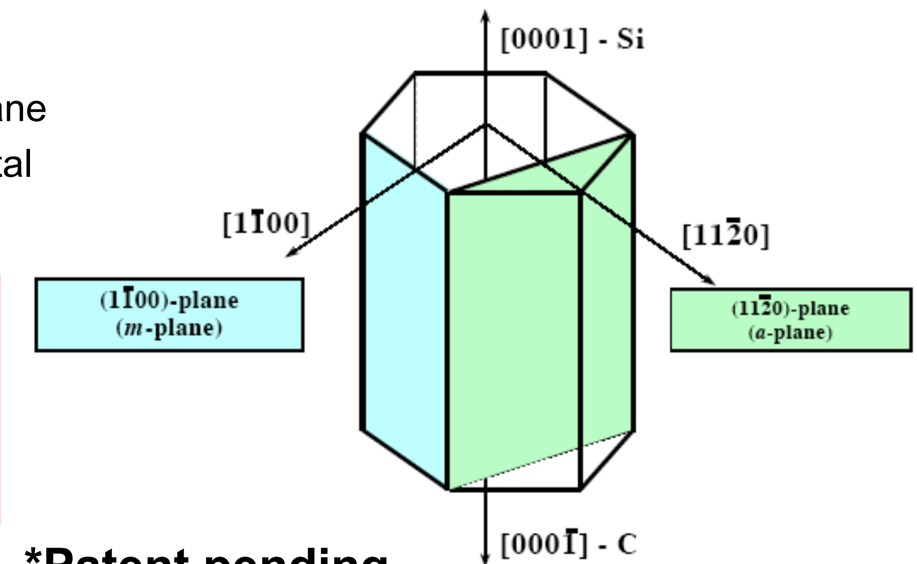

SiC offers the possibility of high voltage, high current operation at elevated temperature with long lifetime and low jitter

***Patent pending**

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SiC switch demonstrates fast operation*

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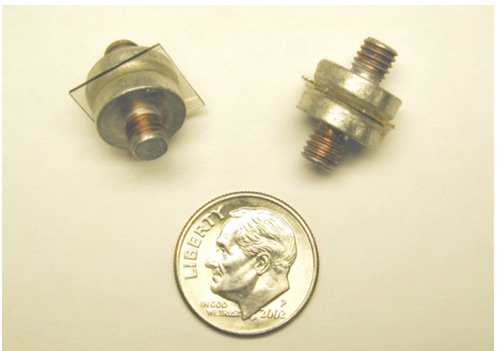
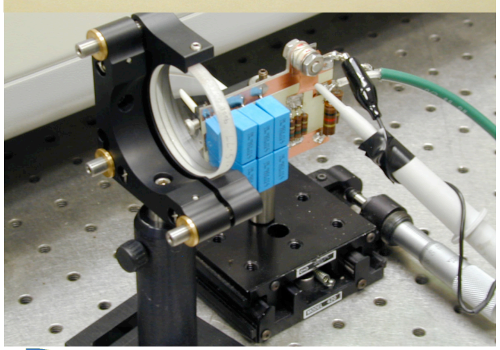
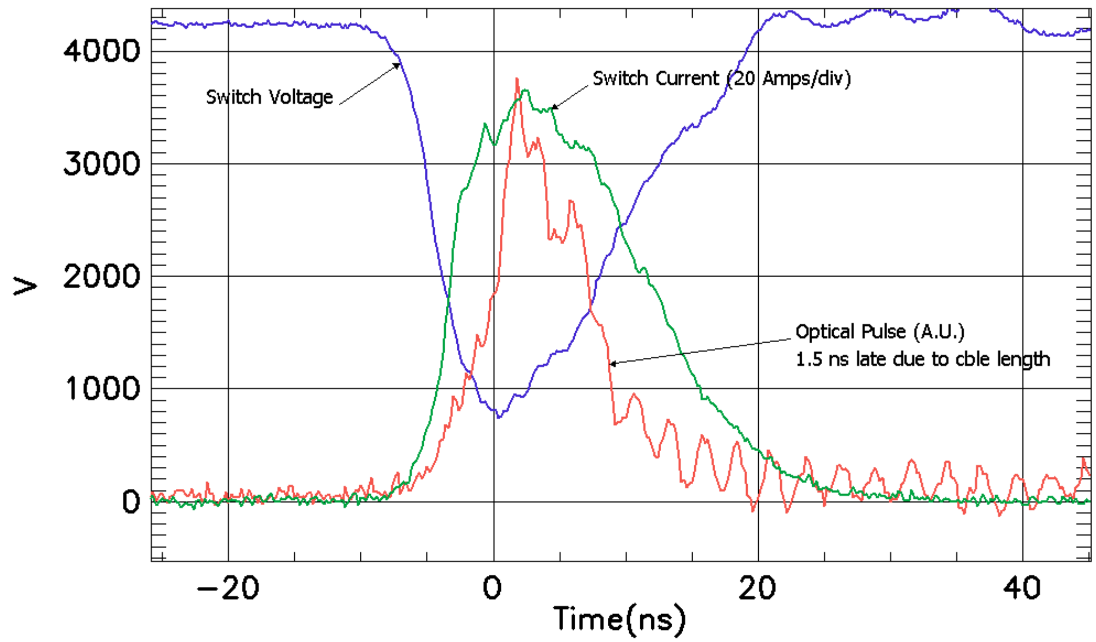
- **SiC photoconductive switch that closes AND opens promptly has been demonstrated at 27.5 MV/m gradient**







*** Patent pending**

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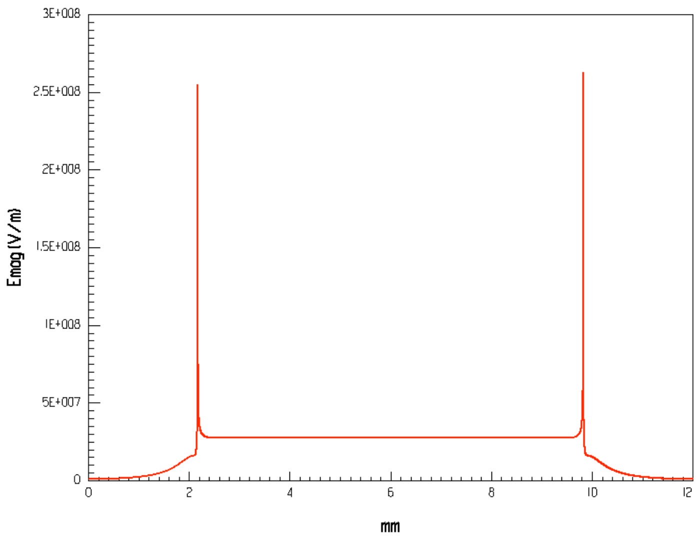
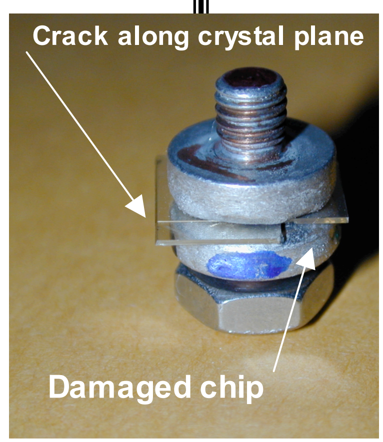
Beyond 27 MV/m, field enhancements must be managed at triple junction interface

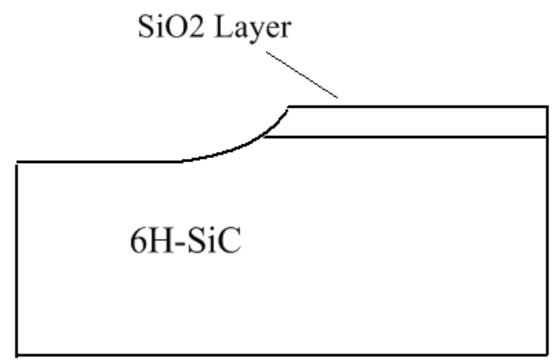
Large enhancements are present at electrode interface

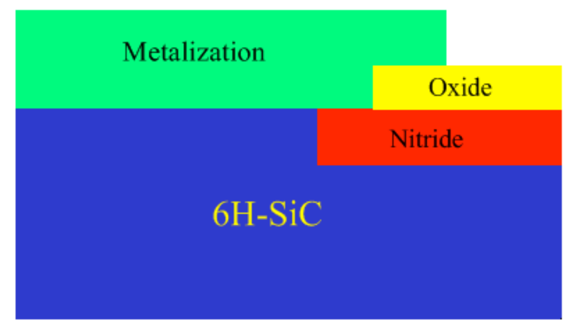


Switch failure at 11 kV



Modified electrode geometries are being pursued for increased gradients*





*** Patents pending**

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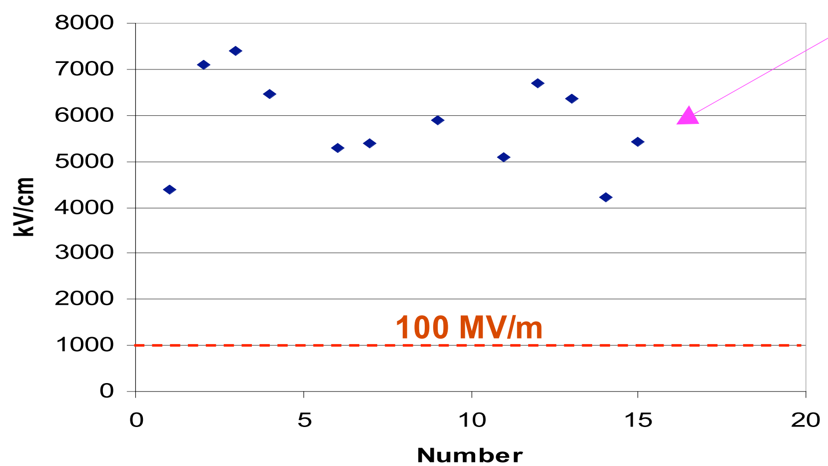
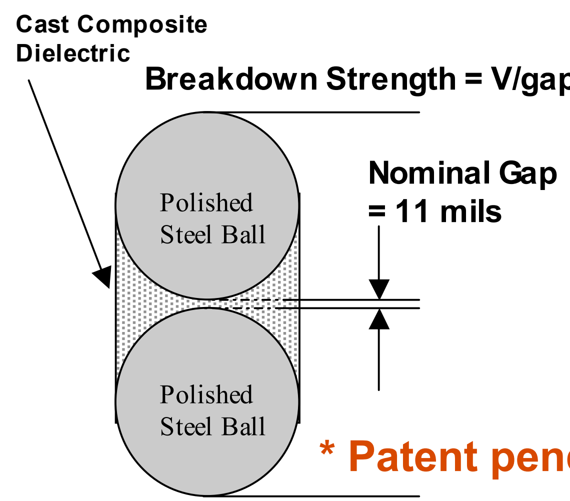
A`new castable dielectric is one of the possible materials for a DWA*

Cast dielectric has high bulk breakdown strength > 400 MV/m (small samples) and can have epsilons from ≈ 3 up to ≈ 50 for transmission lines

ε_r = 45, 1 meter length





*** Patent pending**

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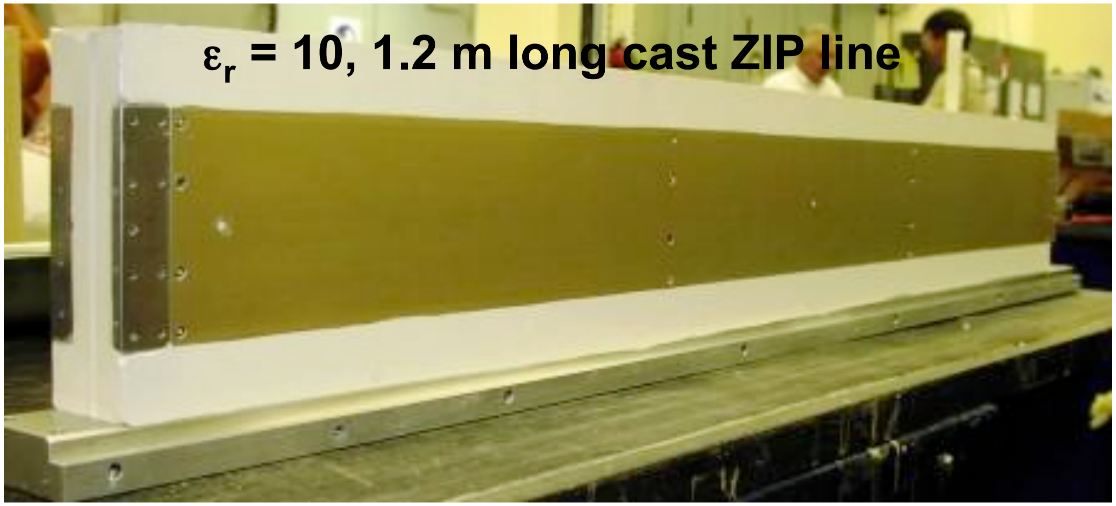
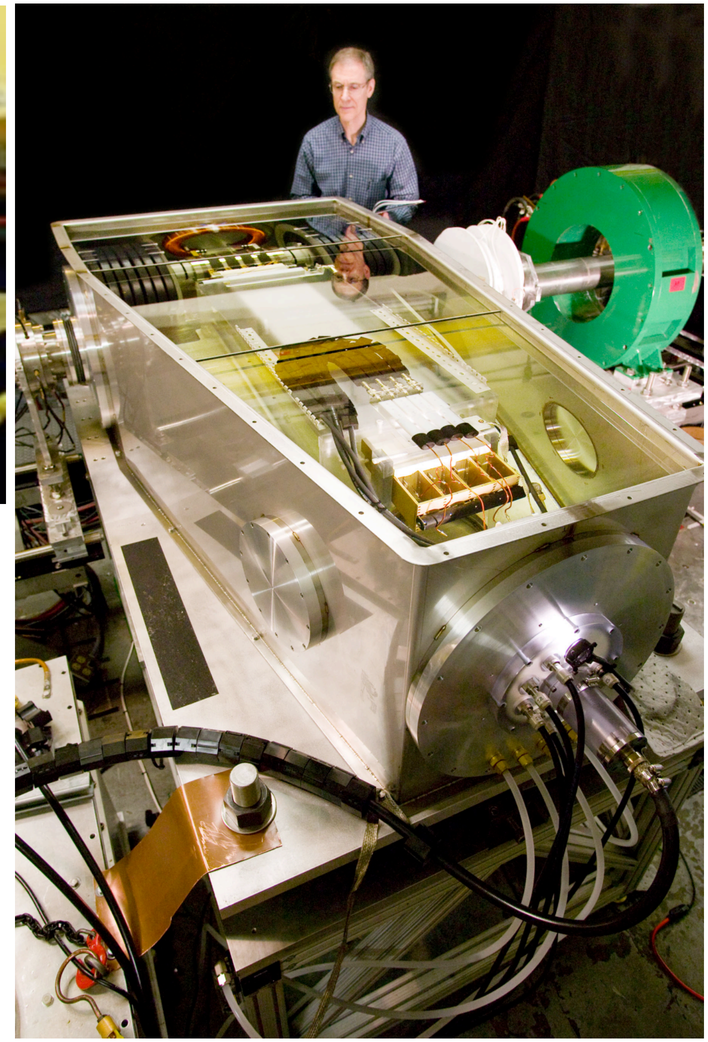
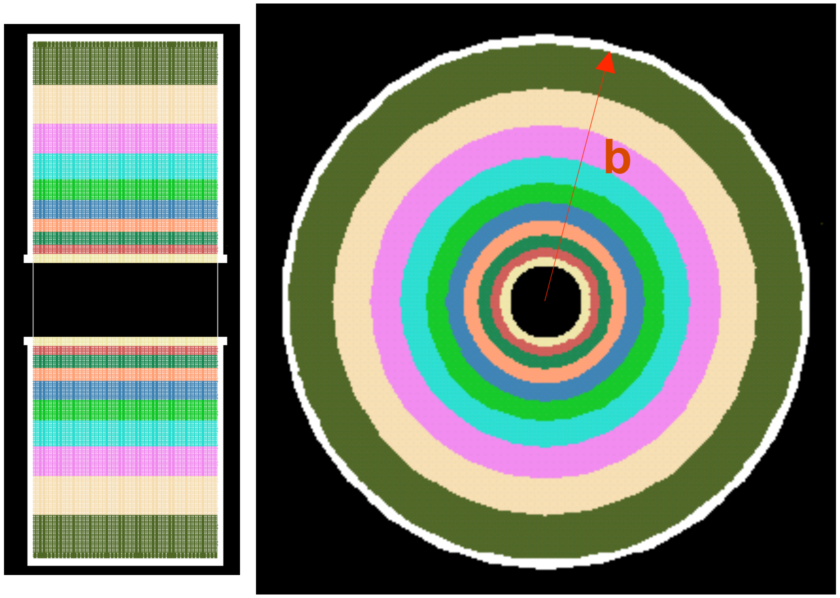


- **Prototype single arm cell**
  - **4 cast dielectric zero integral pulse generating lines producing 25 ns pulse**
  - **4 self-breaking oil switches**
  - **Power coupled to beam through 4 high gradient insulators**
  - **3 MV/m gradient across stack and HGI's with 1 kA electron beam load**



Cast dielectric opens up new possibilities for cell architectures*



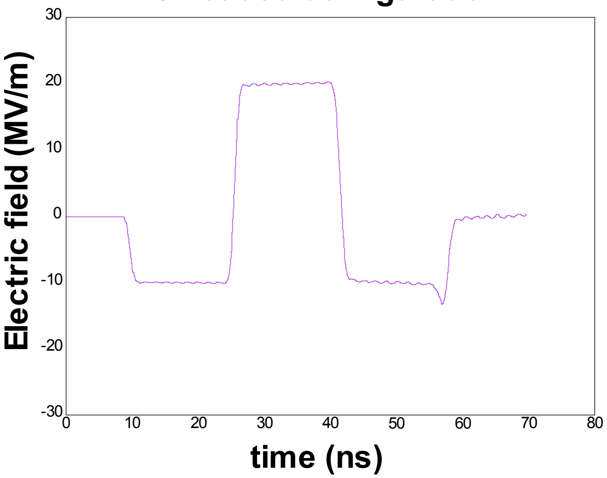
Constant impedance radial ZIP line

$$Z(r) = \frac{60w(r)}{r}\sqrt{\frac{\mu(r)}{\varepsilon(r)}}$$

example: vary relative ε only or relative μ only

$$\varepsilon(r) = \varepsilon_{\min}\left(\frac{b}{r}\right)^2 \qquad \mu(r) = \mu_{\max}\left(\frac{r}{b}\right)^2$$

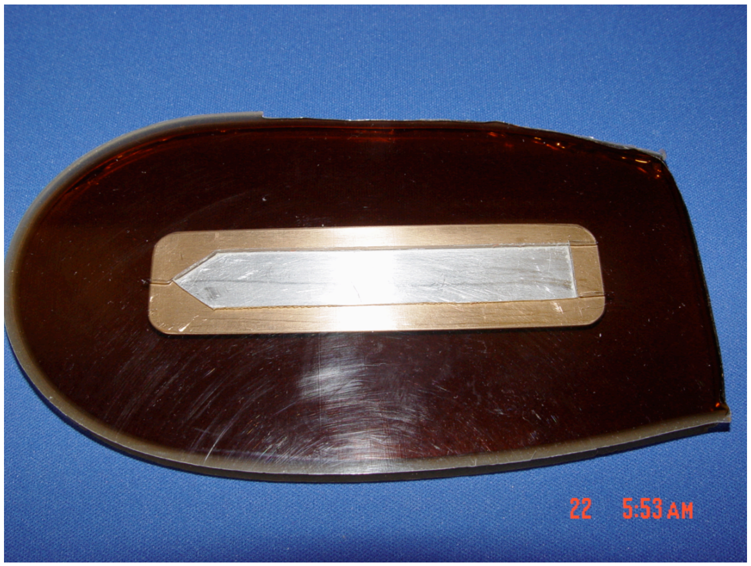
Radial ZIP line, 30MV/m charge
Unloaded configuration

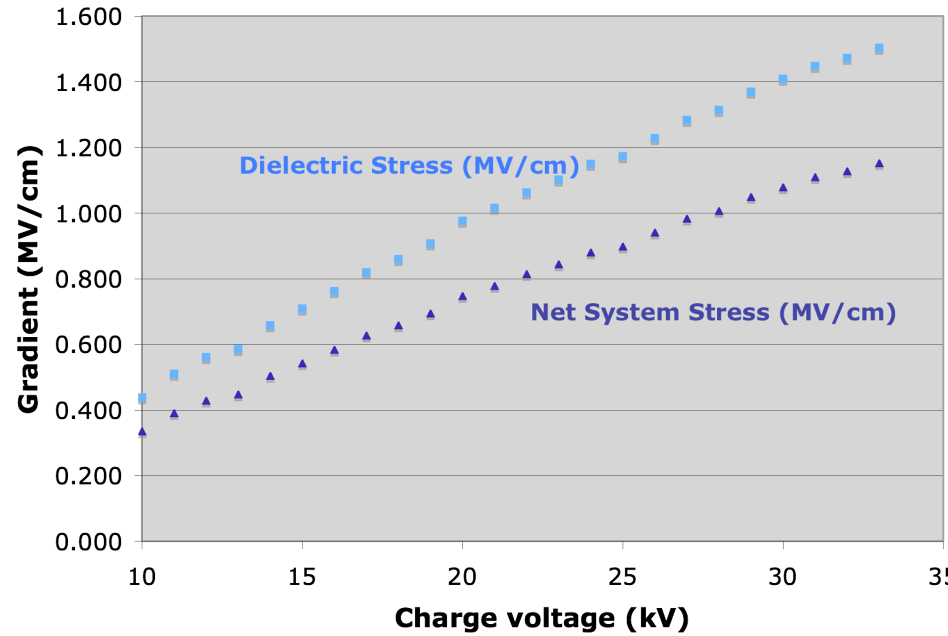


- varying ε, μ and width of lines with radius such that Z(r) is constant results in distortionless transmission

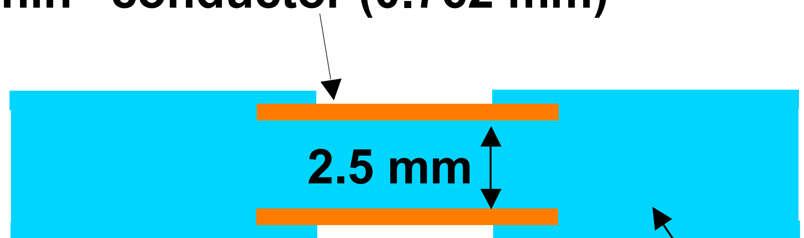
* Patents pending

Embedded electrodes can withstand 100 MV/m





"Thin" conductor (0.762 mm)



Dielectric

- **System gradient > 100 MV/m (counting electrode thickness)**
- ***Performance for a thinner (SiC) configuration should be better***

We have been investigating the potential application of the DWA to cancer therapy

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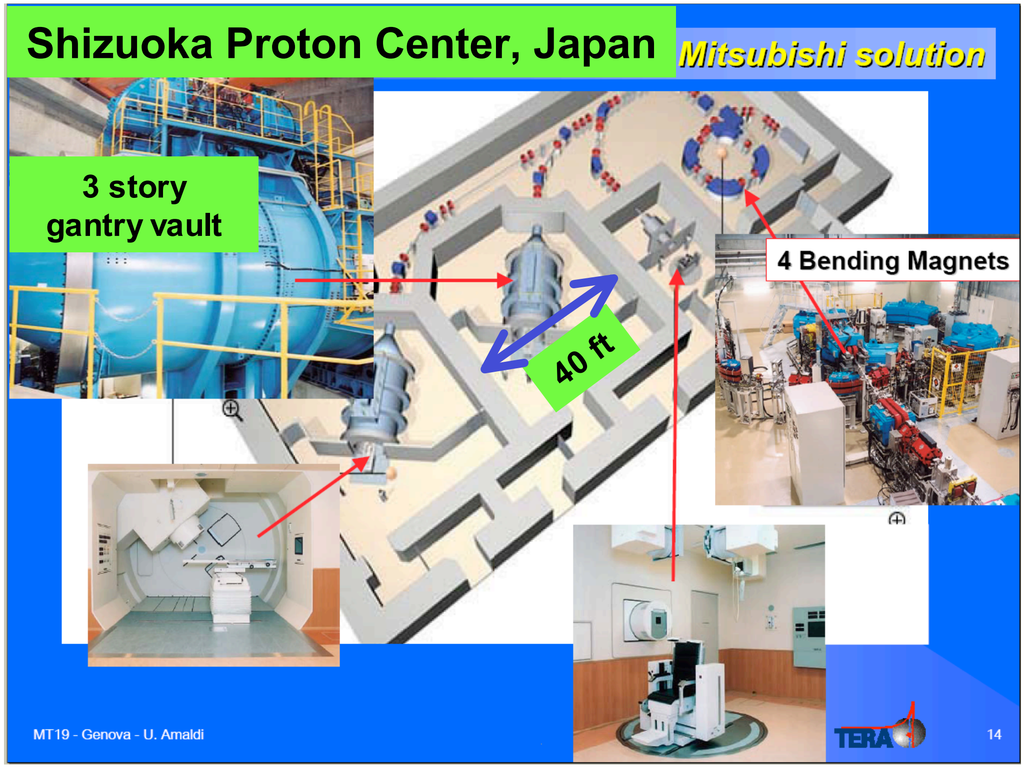

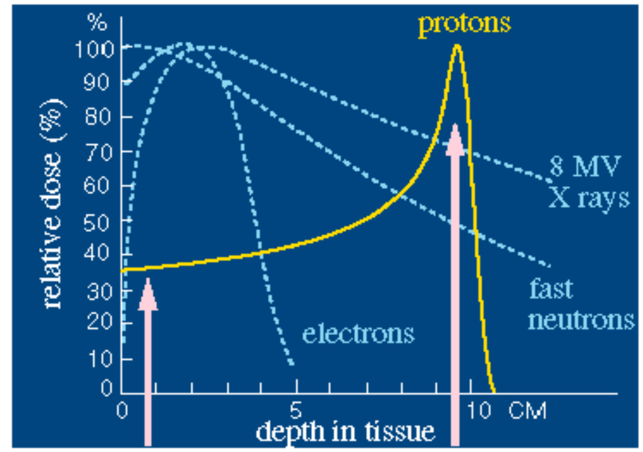

- **Bragg peak minimizes damage to normal tissue**
  - **Requires 70 - 250 MeV at ≈ ten nanoamperes average current**
- **Current space requirements preclude use in most hospital facilities; large capital investment required**

X-ray treatment machines fit in a single room - <u>this is our goal for a compact proton machine</u>

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DWA can be used in the sequential pulse traveling wave mode*

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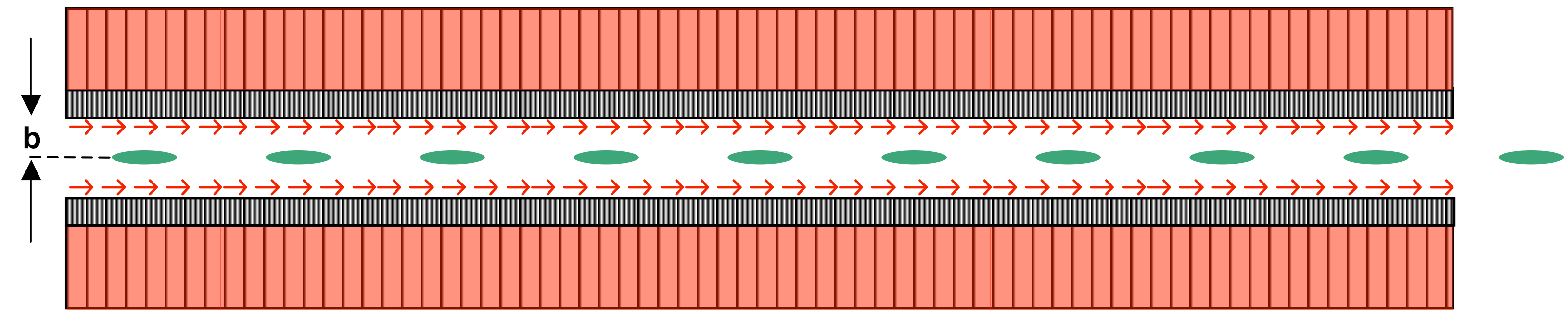
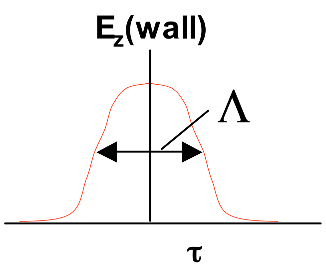
HGI characteristics imply that the highest gradients will be attained for the shortest pulses



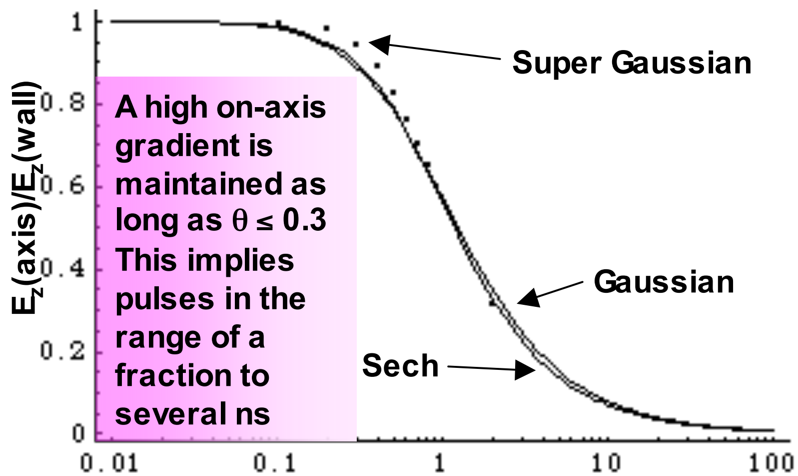
Along the wall $E_z(r,t,z) = E_z(r,\tau)$

$$\tau \equiv t - z/u$$



$$\gamma = \frac{1}{\sqrt{1-u^2/c^2}}$$

Λ = full width at half maximum
u = speed of wall excitation
γ = Lorentz factor



$$\theta \equiv \frac{b}{\gamma u \Lambda}$$

This accelerator can work for any charged particle

*patent pending

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DWA supports a virtual traveling wave by continuous wall excitation*

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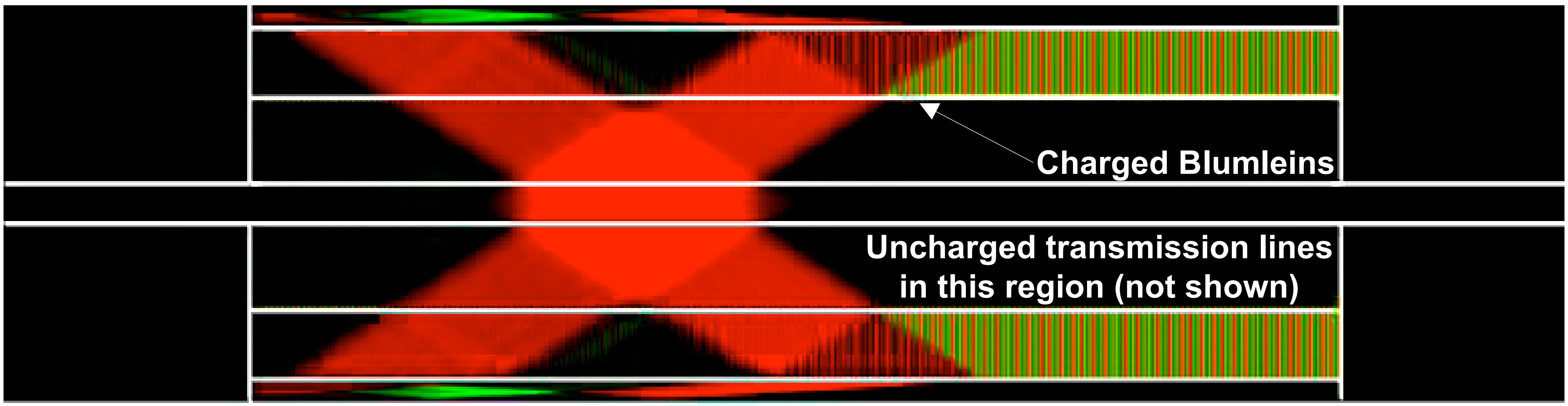
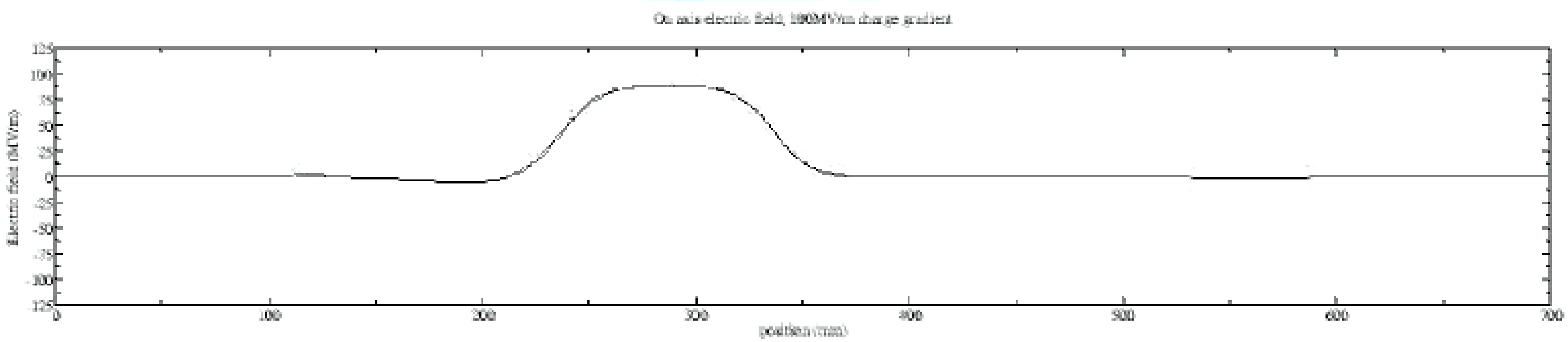
Longitudinal Electric Field Plot





*patent pending

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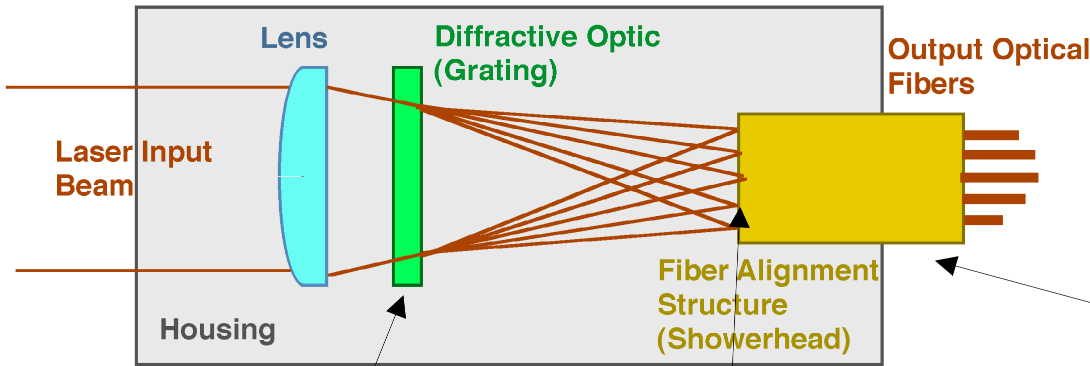
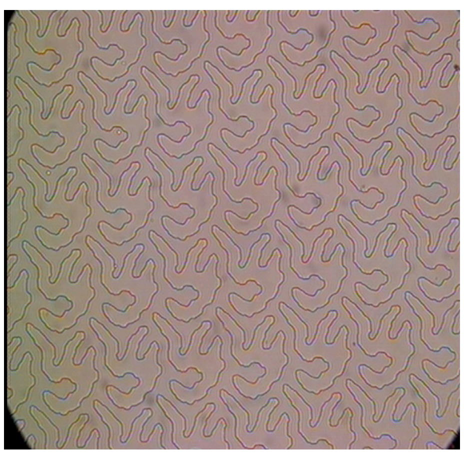
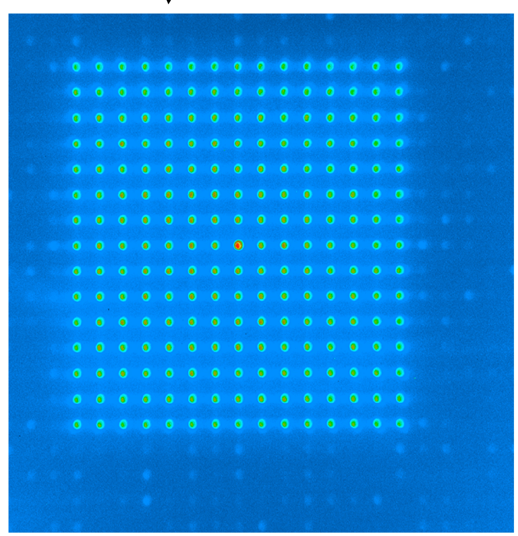
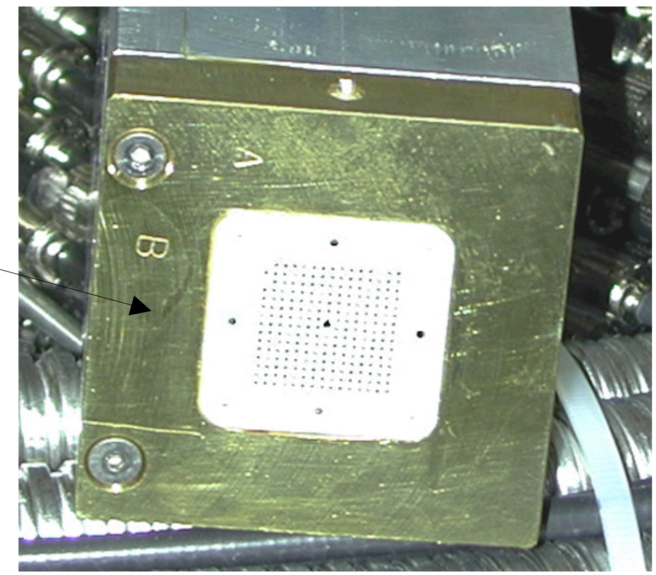
Accelerator timing is set with a fiber optic distribution system

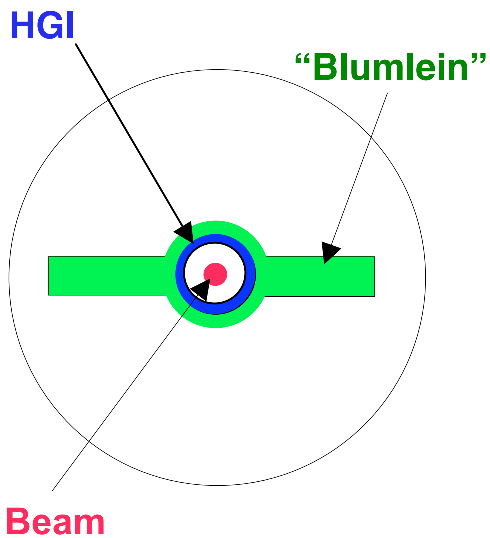


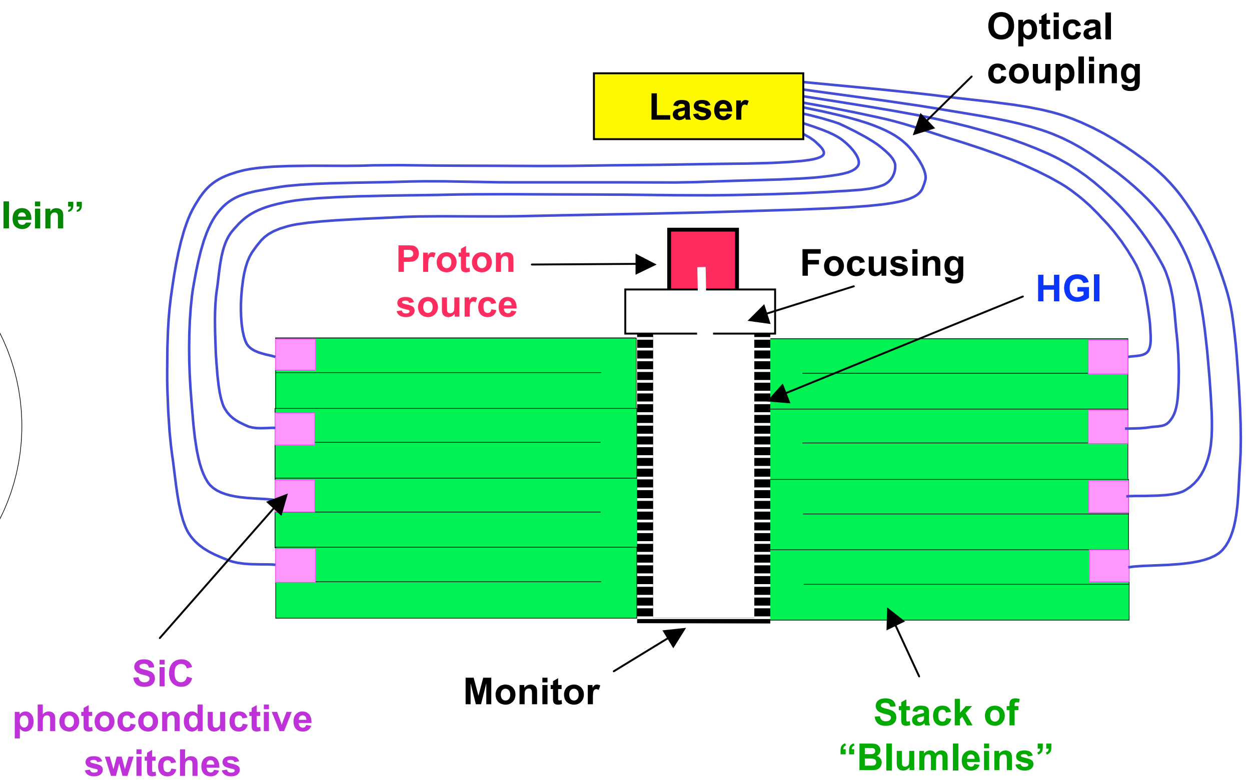






Stacks of “Blumleins” with independent switch triggers implement the virtual traveling wave*





* Patents pending

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Novel source and electrode system provides great flexibility*

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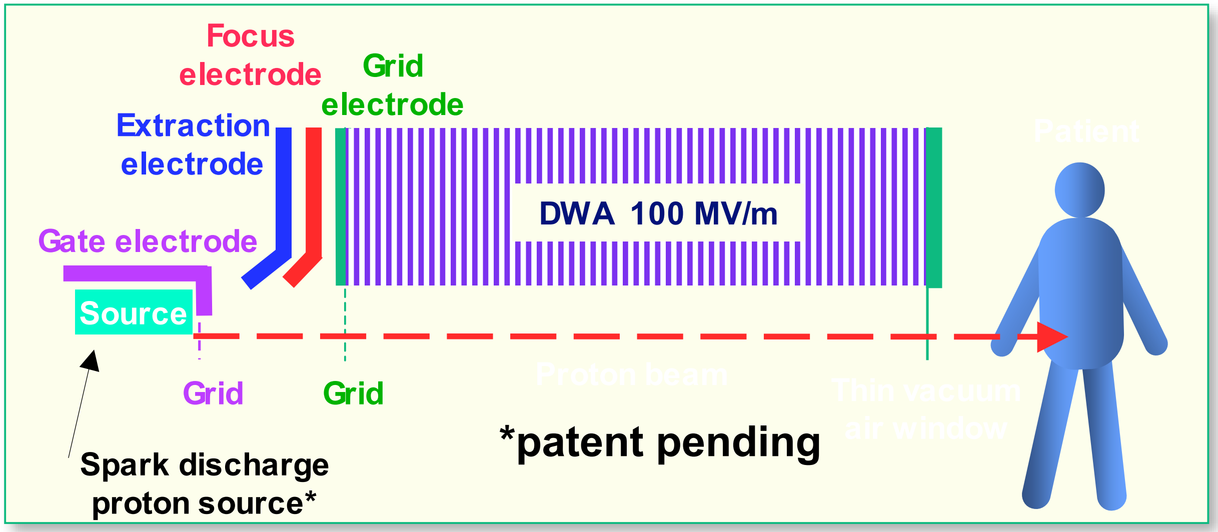

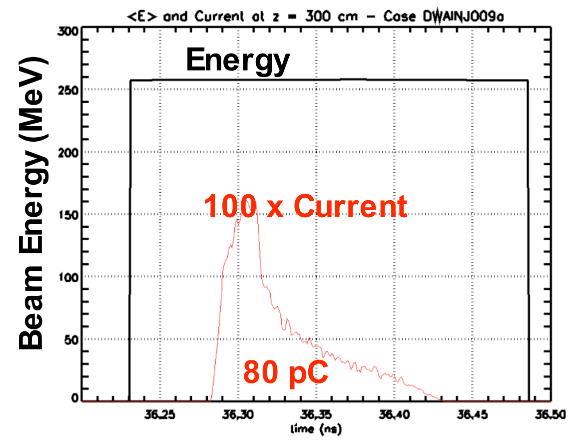

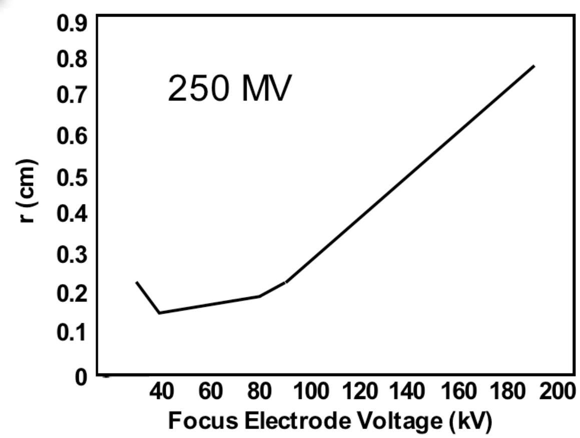

- The DWA proton accelerator uses only electric focusing fields for transporting the beam and focusing on the patient
  - — Wide range of spot sizes (2 mm - 2 cm diameter) can be obtained for 70 - 250 MeV proton energy - varied on each pulse
  - — Variable beam current on each pulse
  - — Variable beam energy on each pulse

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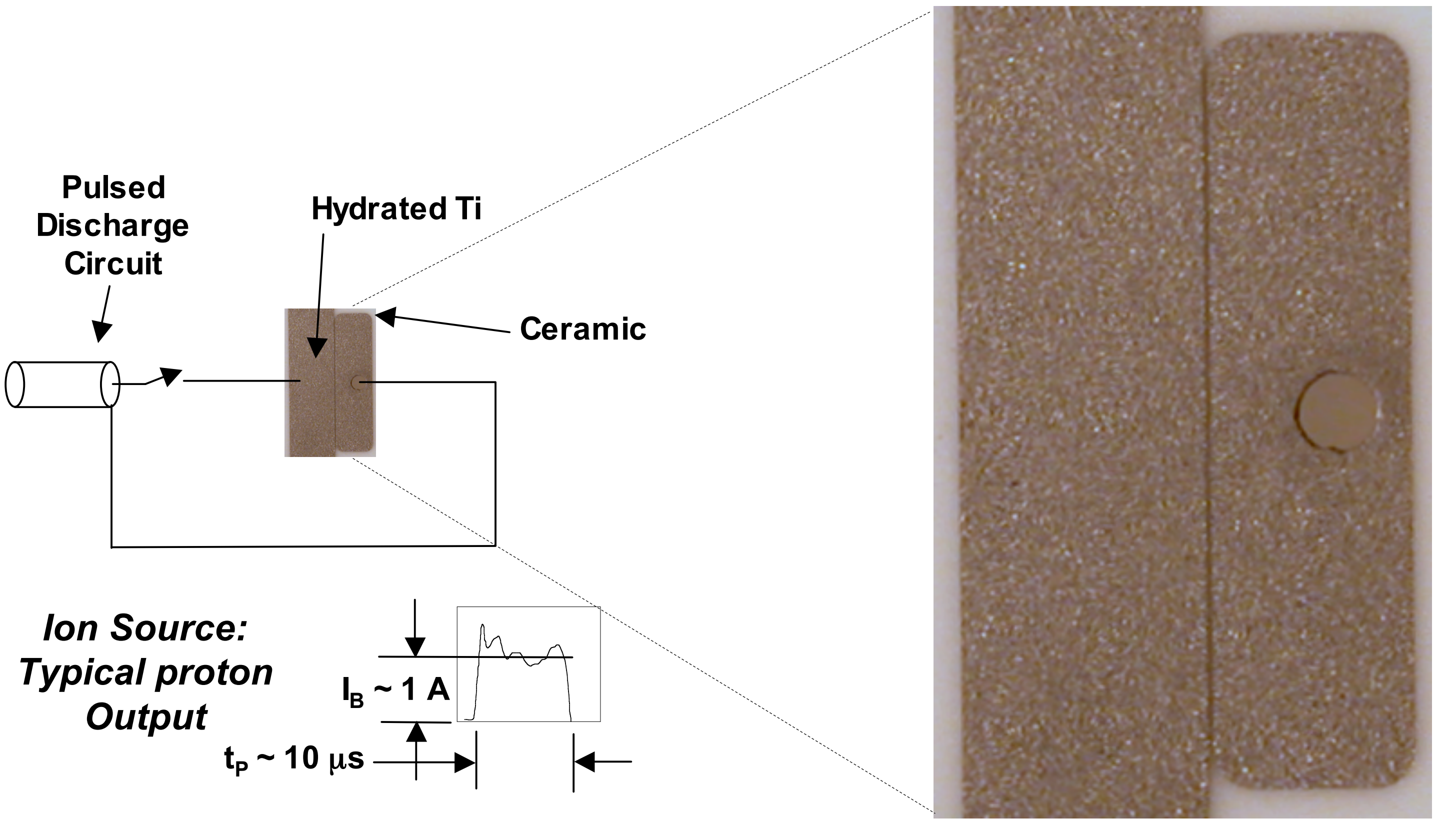
Spark discharge proton source is very compact*



*patent pending

Beam capture into the DWA for a nearly ideal waveform*

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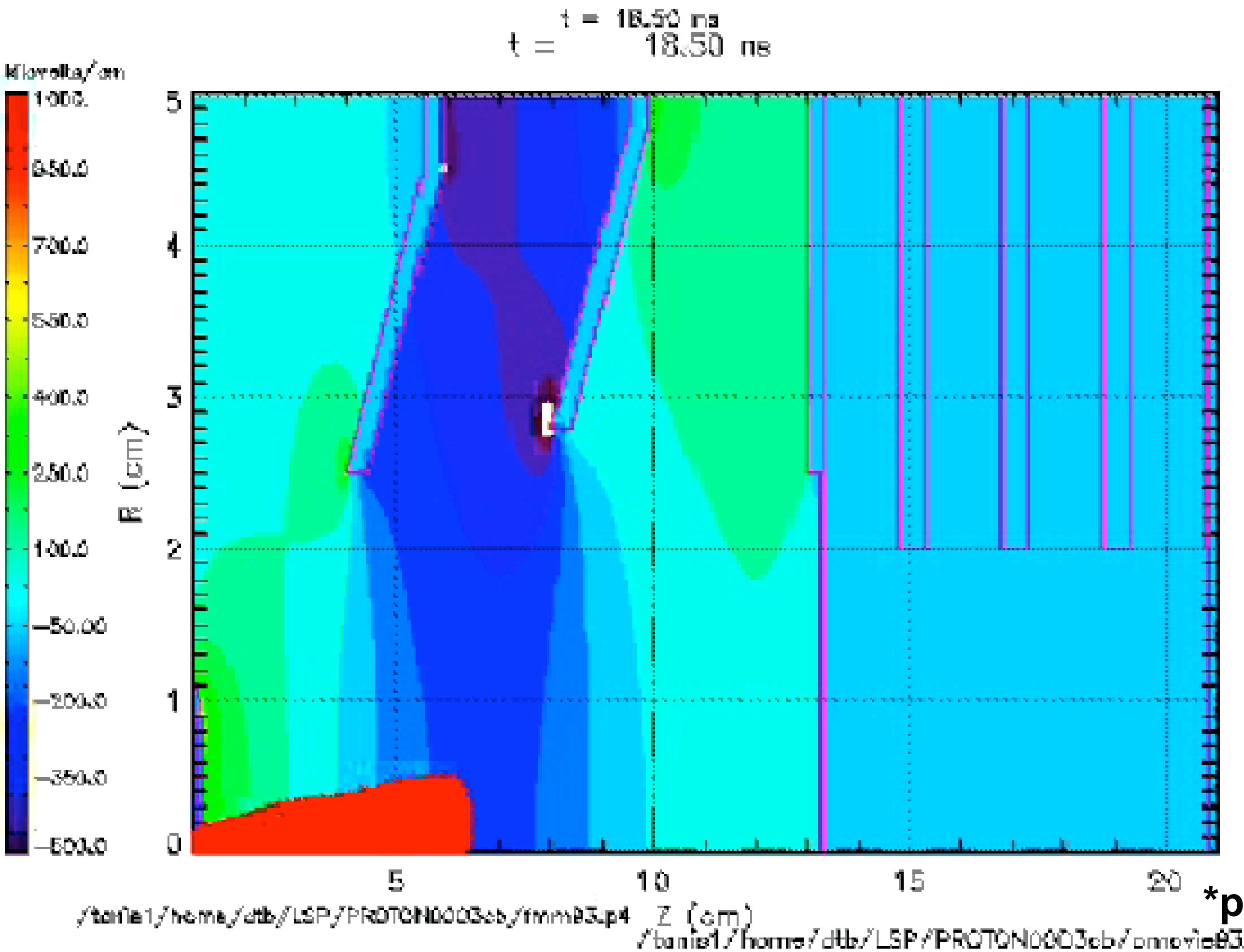

*patent pending

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Compact proton accelerator can provide active scanning without sweeping magnets*

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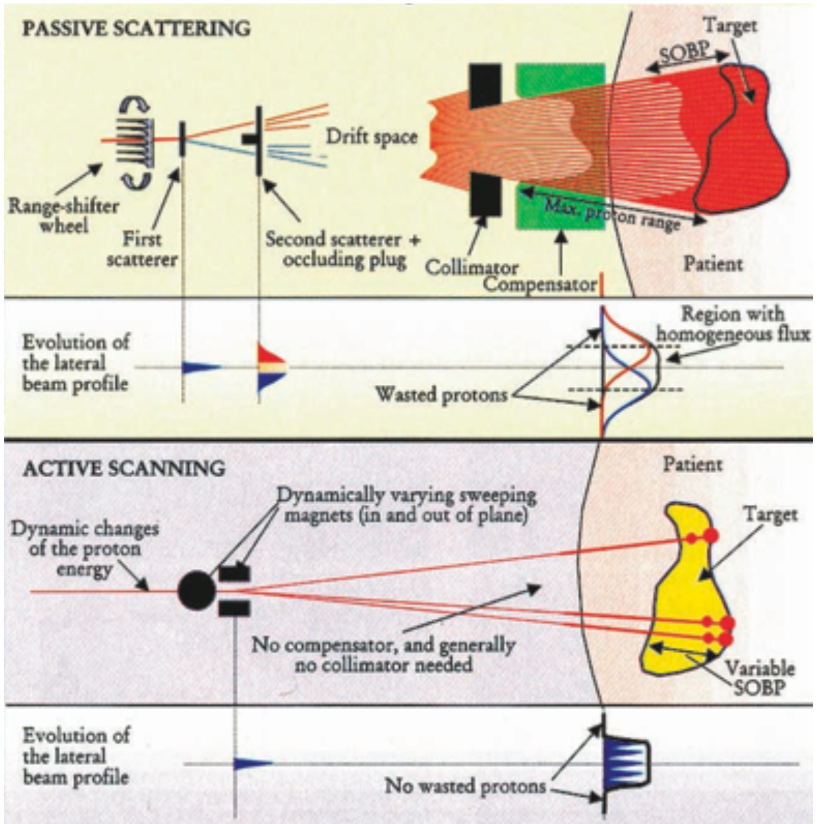
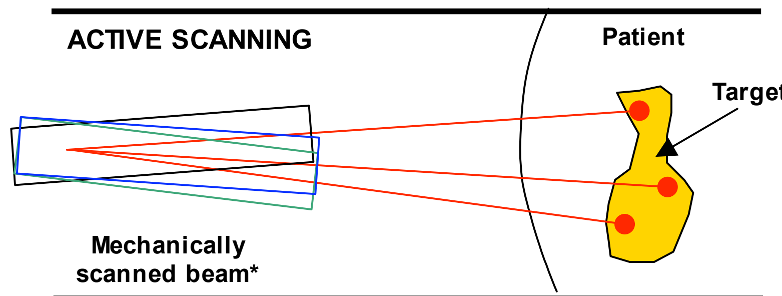
Conventional Techniques**



Compact Accelerator Technique

- minimal beam interception
  - electronically adjusted range
  - minimum length arrangement
- lower beam current
  - less radiation
  - less residual activation
  - less shielding required



* Patent pending

** Goitein, M., Lomax, A., Pedroni, E., "Treating Cancer With Protons", Physics Today Sept. 2002, pg. 45

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Compact proton radiotherapy system concept*

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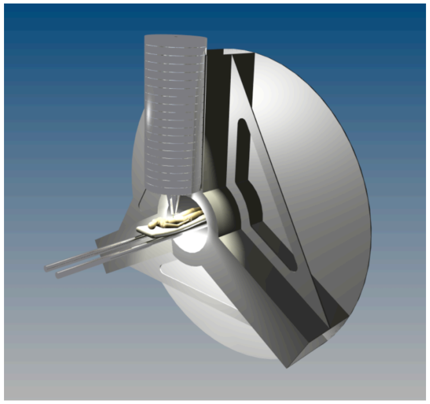
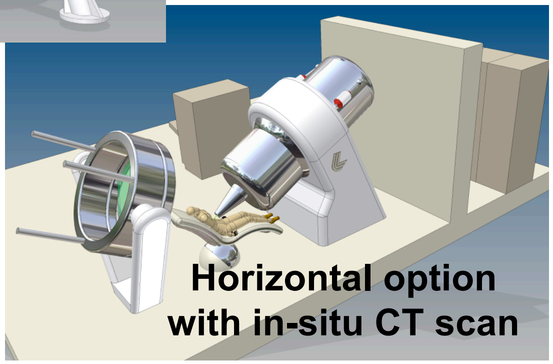
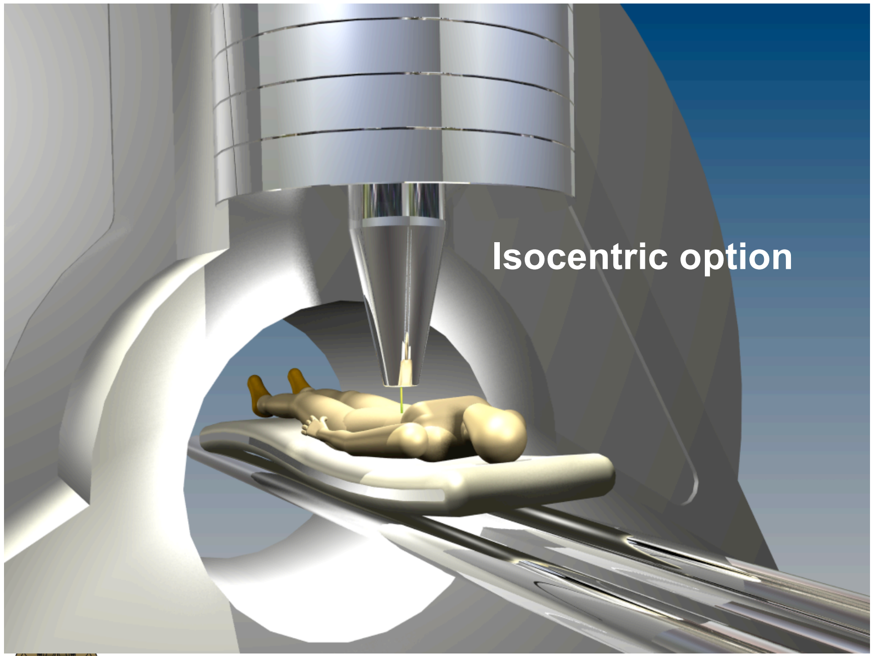
- Pencil beam can be *mechanically* scanned in x and y
- Flexible dose delivery via pulse-to-pulse variable energy and intensity
    - Energy range 70 - 250 MeV
- Multiple patient delivery configurations possible to accommodate available space



* Patent pending





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We are working with Tomotherapy, Incorporated to develop a compact proton DWA

- System will provide CT-guided rotational IMPT
- Goal is to fit machine in a standard linac radiation vault
- The beam intensity, spot size and energy can be varied from pulse to pulse without the use of any beam intercepting methods
  - No range shifting wedges or scattering masks
- TomoTherapy has licensed the DWA technology from the Lawrence Livermore National Laboratory and has a Cooperative Research and Development Agreement (CRADA) with LLNL

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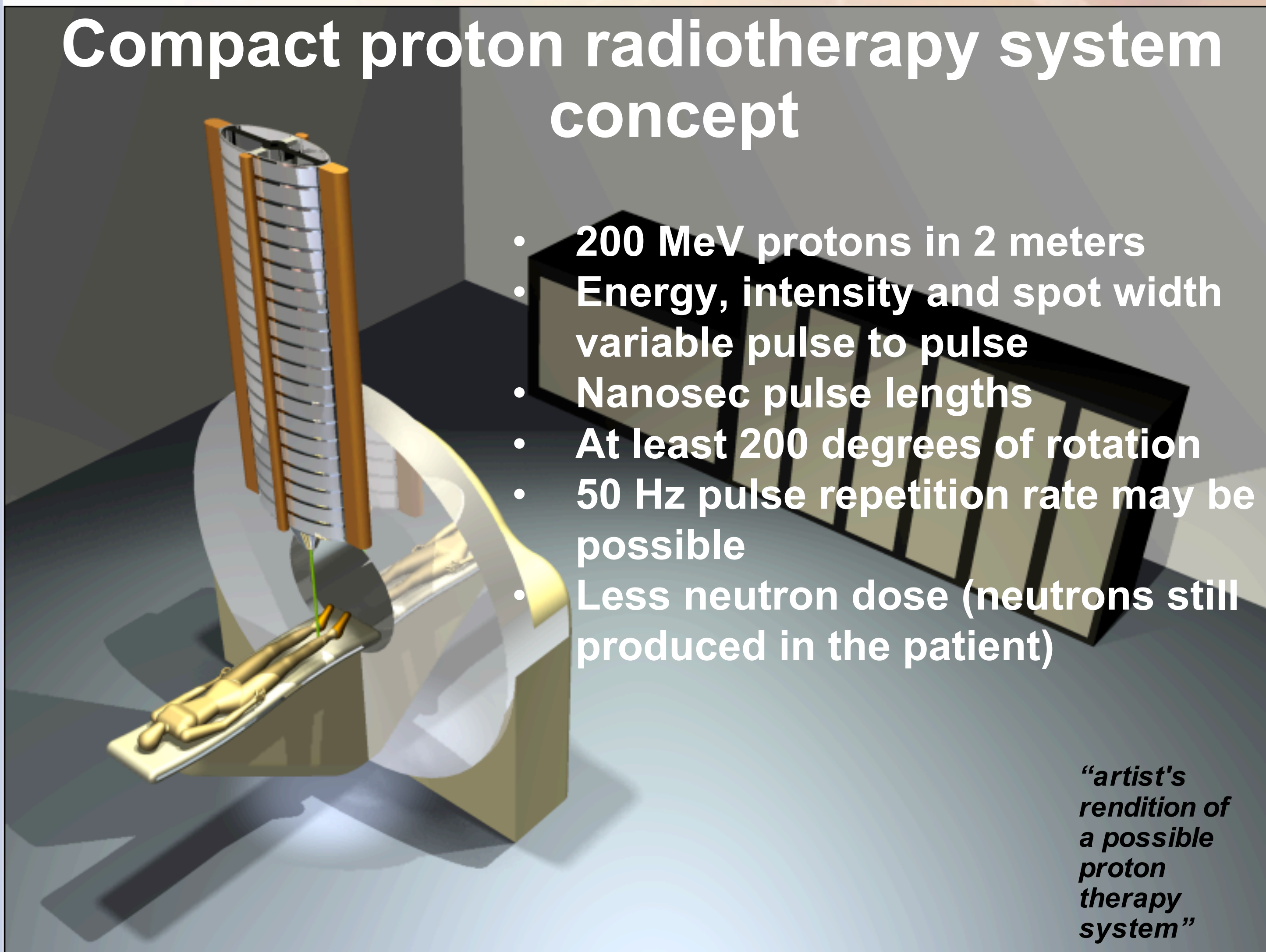
Compact proton radiotherapy system concept



- 200 MeV protons in 2 meters
- Energy, intensity and spot width variable pulse to pulse
- Nanosec pulse lengths
- At least 200 degrees of rotation
- 50 Hz pulse repetition rate may be possible
- Less neutron dose (neutrons still produced in the patient)

“artist's rendition of a possible proton therapy system”

R&D issues for a high current, longer pulse system

- HGI - what is the reliable working gradient that can be sustained
  - Length scaling to very large excitation lengths (≈ 3ns x c)
- SiC switches
  - Optical power required for triggering
  - Laser system
  - Optical distribution system
- Proton injector
- How to add focusing with minimum impact on gradient

Limited length scaling will be tested with HV pulser

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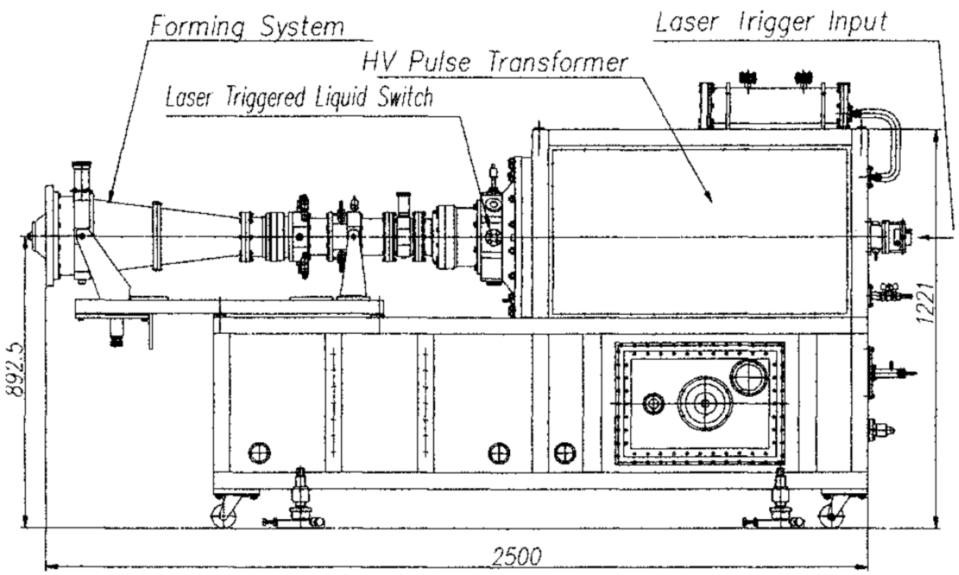
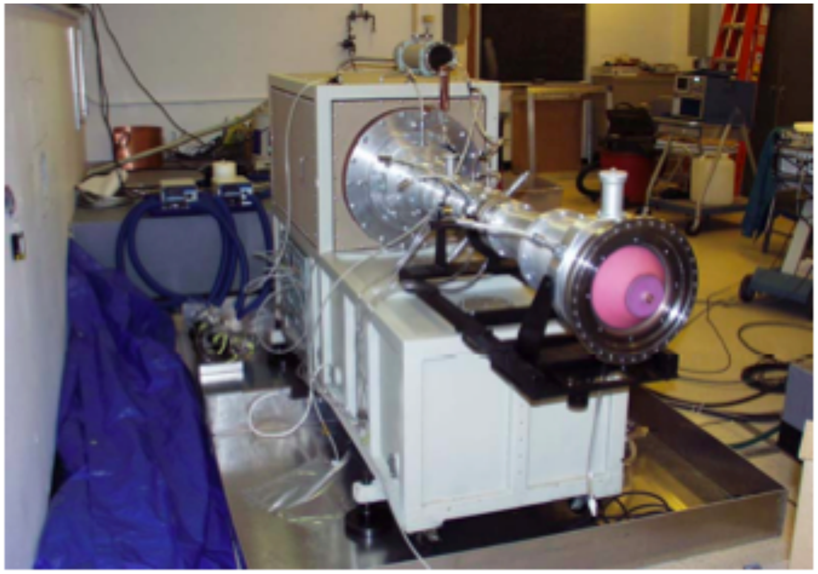
- Delivers 3-5 MV into a 160 Ω matched load, 1~2 ns pulse
- Will permit testing of hollow insulators at full radial scale





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Near term plans for proton accelerator development

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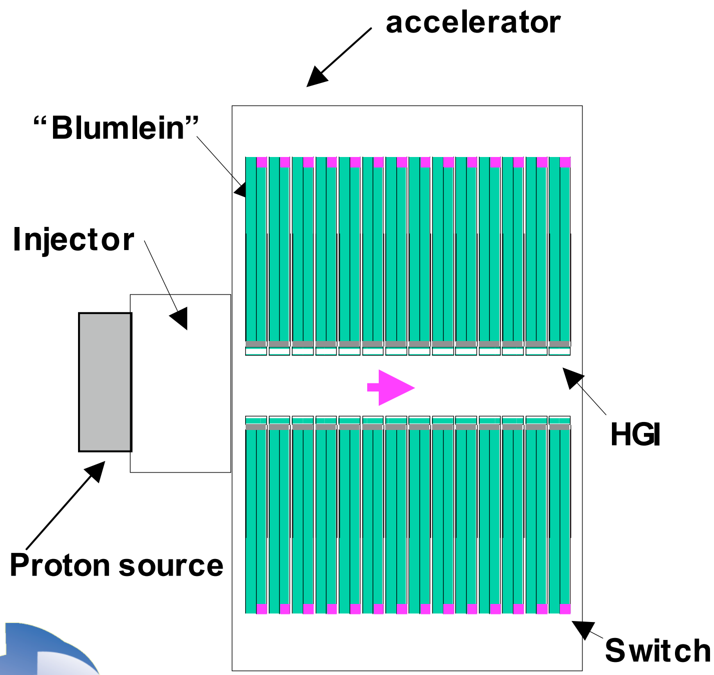
- We are working towards development of a subscale prototype over the next 10 months
  - A small length of accelerator sufficient to verify the accelerator architecture and HGI performance with SiC switches



- Over the next 10 months we will be testing individual components to assess performance limits
  - Solid dielectrics
  - Photoconductive switches
  - High gradient insulators

- Subscale prototype (≈ 10 cm) ready for test in 10 months

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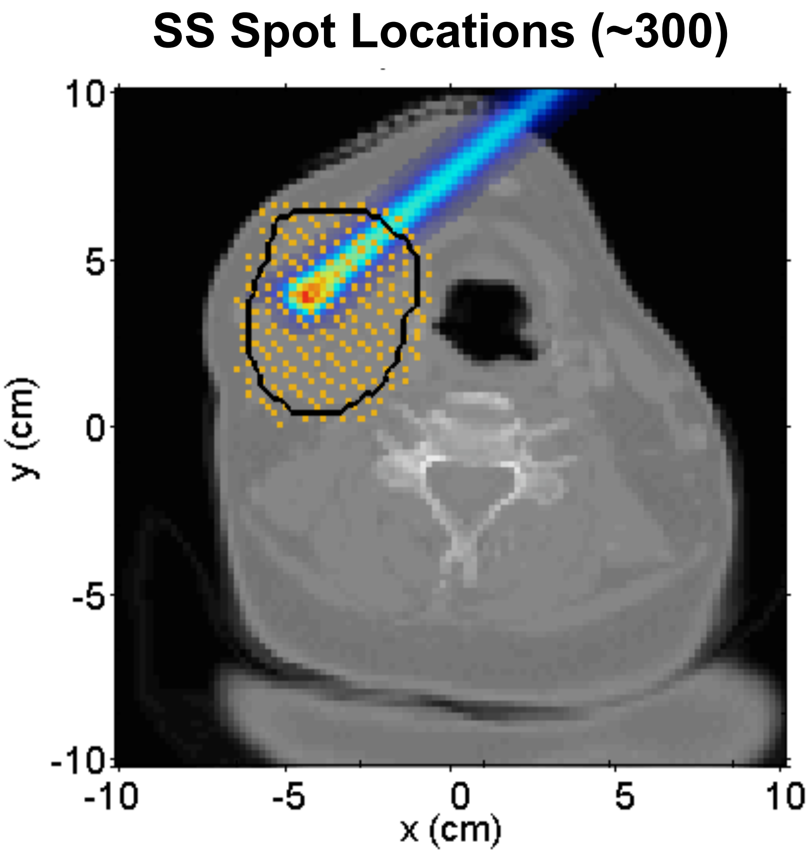
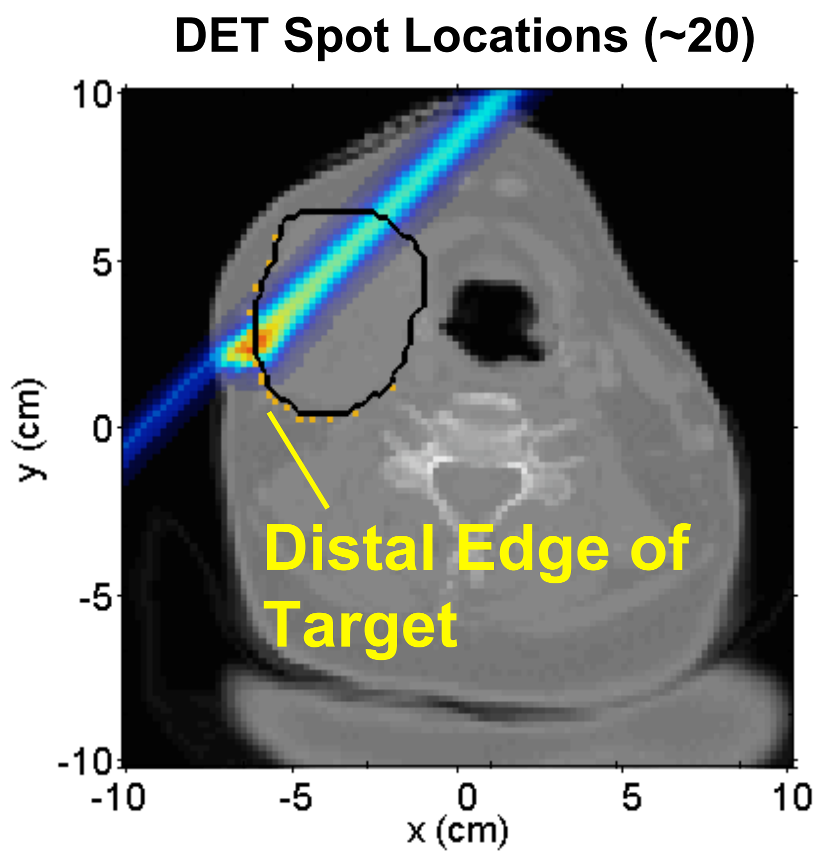
Summary

- **DWA promises to dramatically increase the accelerating gradient of induction accelerators**
- **Good progress is being made on the technologies needed for the DWA**
  - **SiC photoconductive switch (27.5 MV/m stress)**
  - **Pulse forming line dielectric materials (> 400 MV/m)**
  - **High gradient vacuum insulators (up to 100 MV/m)**
- **Compact proton therapy accelerator concept for IMPT has been described**

Spot scanning and distal edge tracking (DET)





- Multiple directions or arc therapy and intensity modulation required to obtain uniform dose distribution

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Spot scanning and distal edge tracking (DET) distributions

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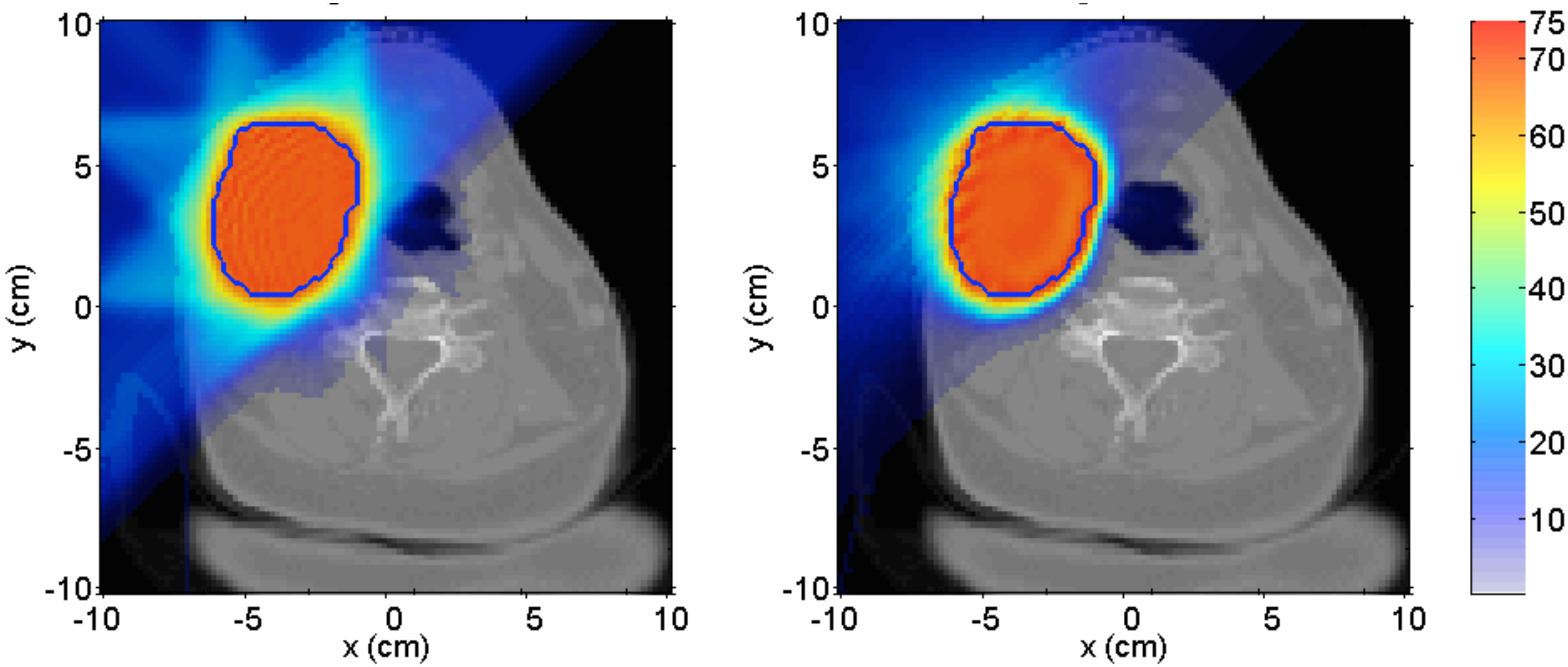
SS Dose Distribution, 5 directions | **DET Dose Distribution, 25 directions**



- DET can be delivered with limited arc therapy

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